# PBH-infused seesaw origin of matter and unique gravitational waves

Rome Samanta, CEICO, Institute of Physics, Prague

NEHOP, Napoli, Italy

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JCAP(2021), JCAP(2022), JHEP(2023), arxiv:2304.11844

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Total slides: 11

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Borah, IITG    Suruj, IITG


New parameter space for ordinary matter + dark matter in seesaw: Thanks to PBHs

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The GW triangle


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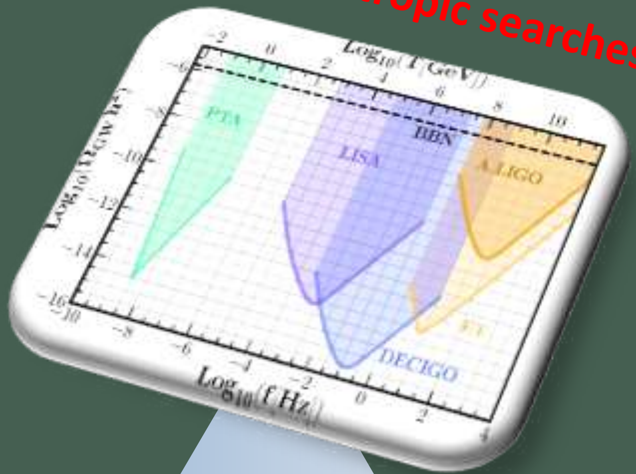
Isotropic searches

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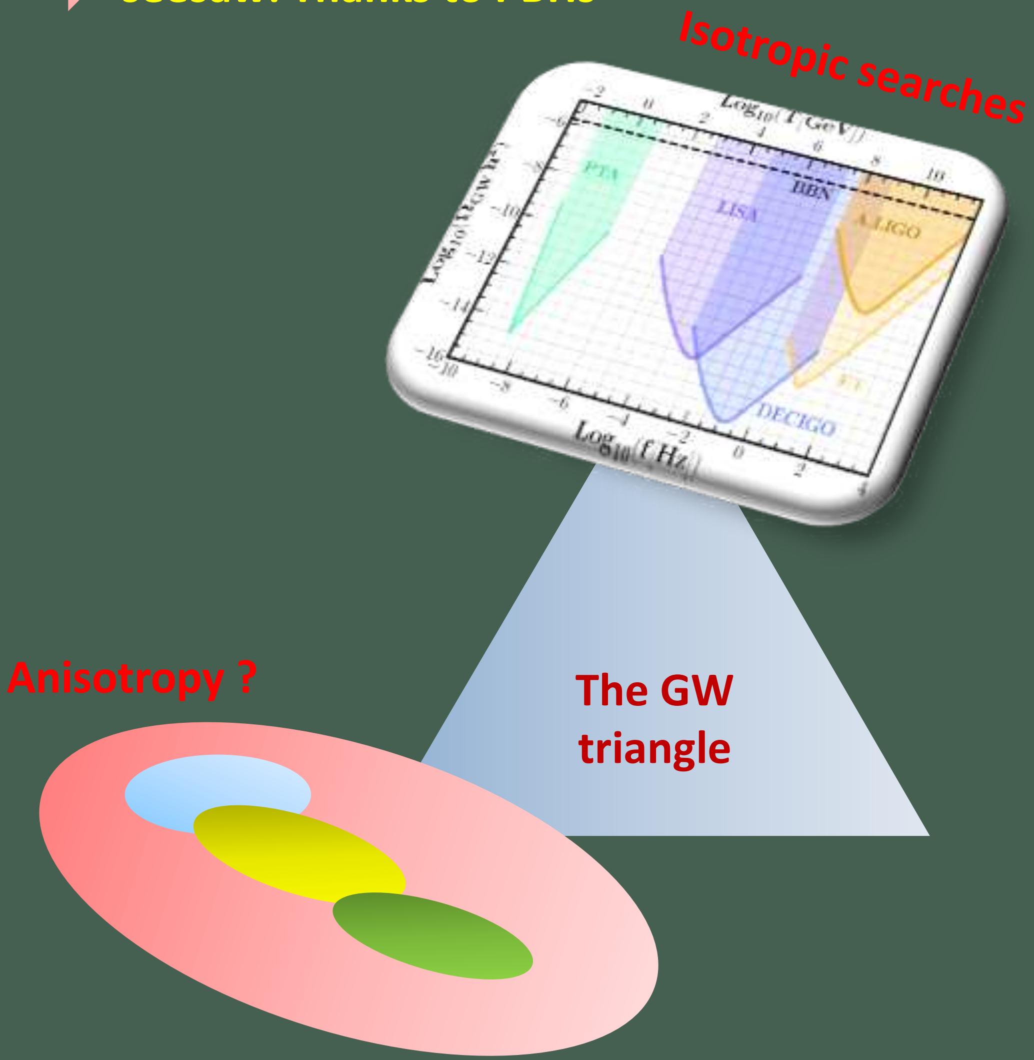



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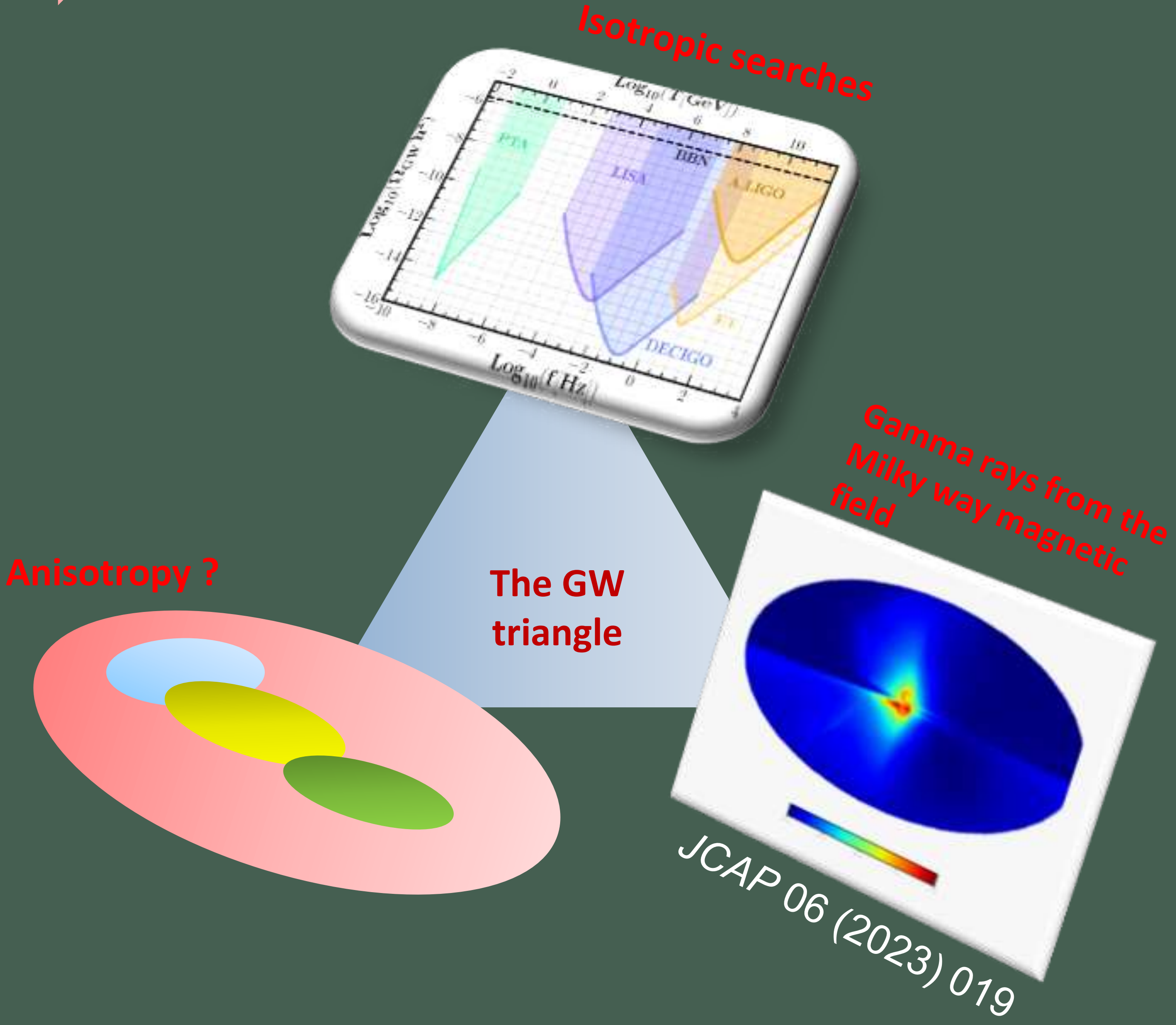


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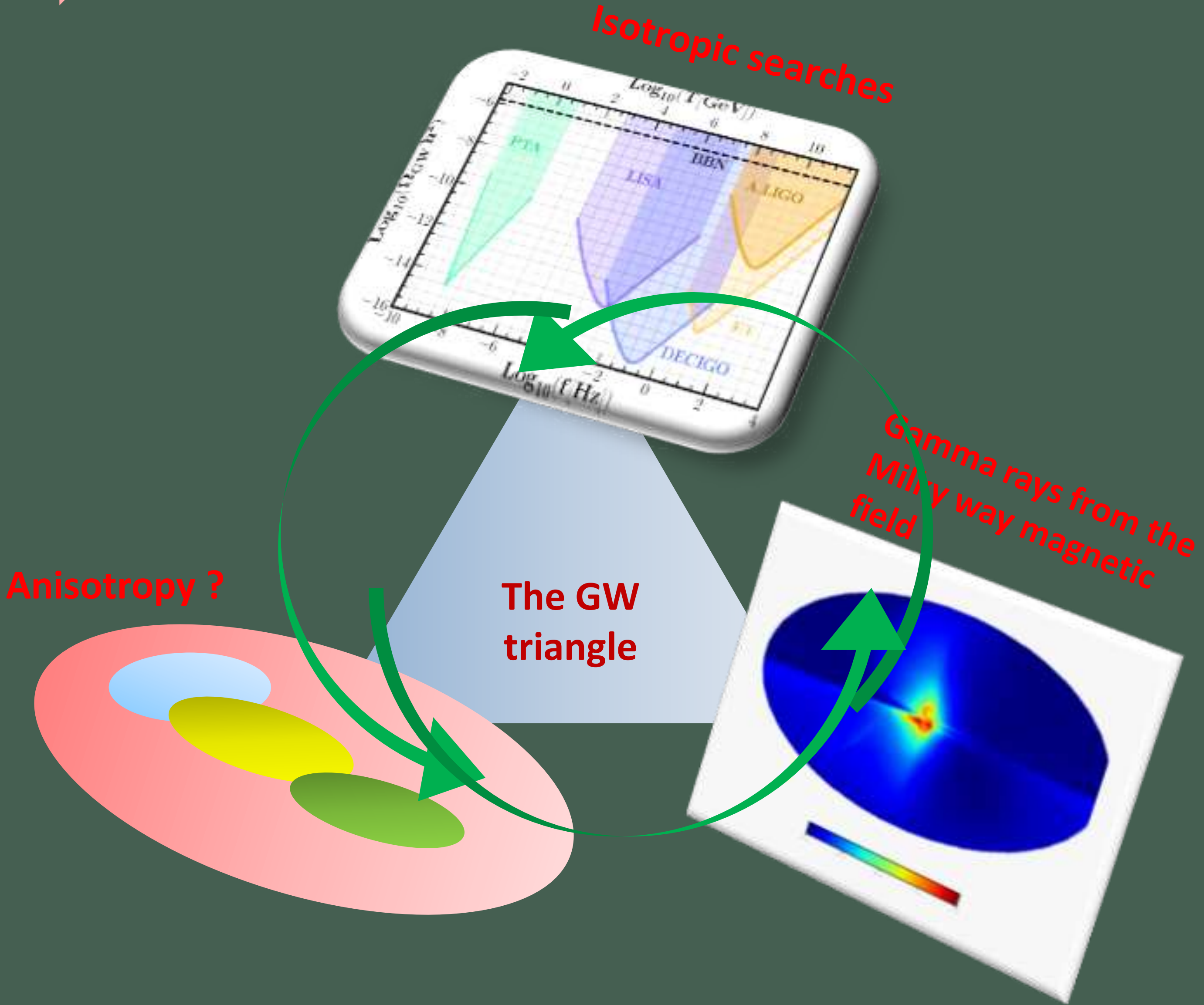



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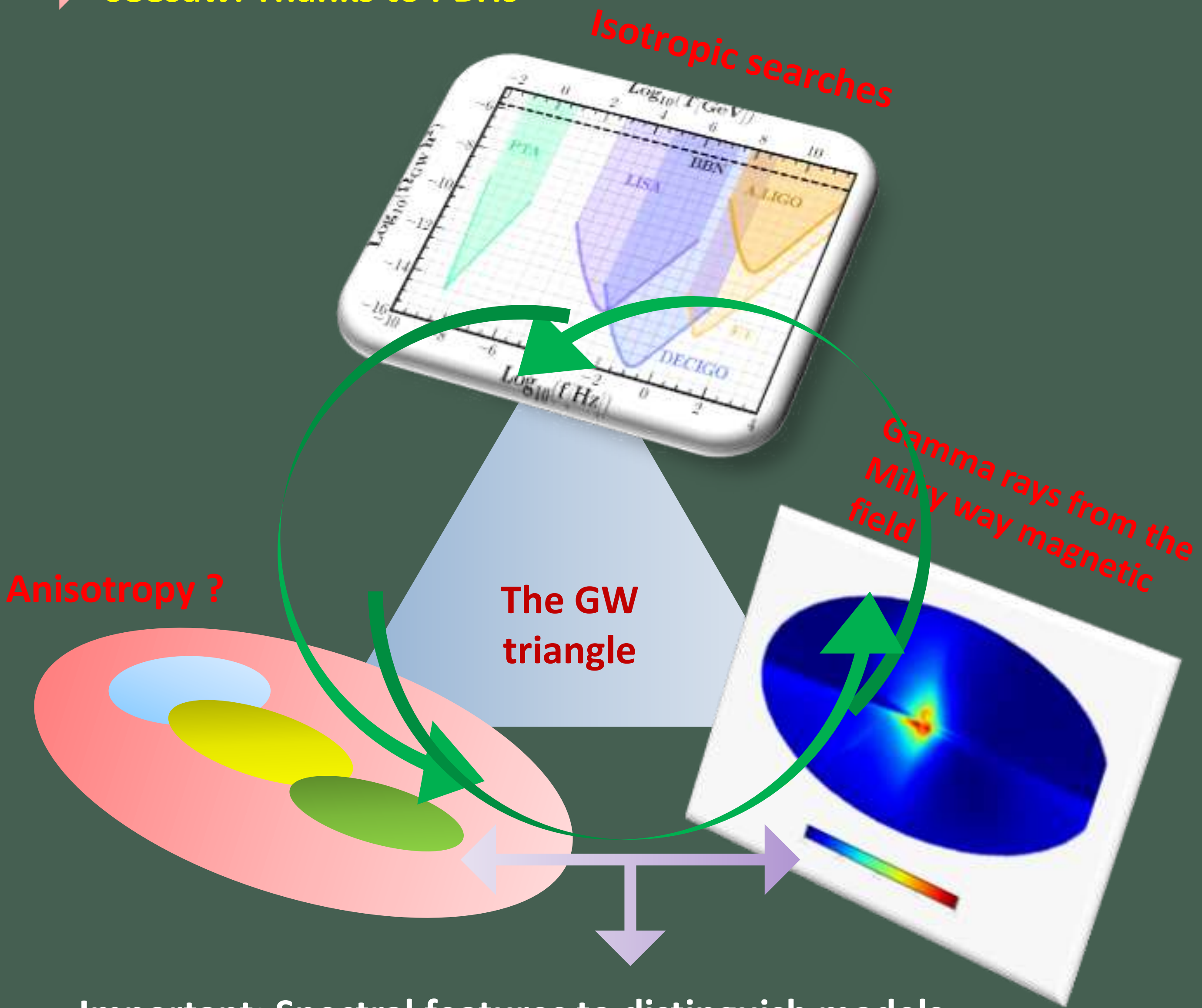



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Important: Spectral features to distinguish models


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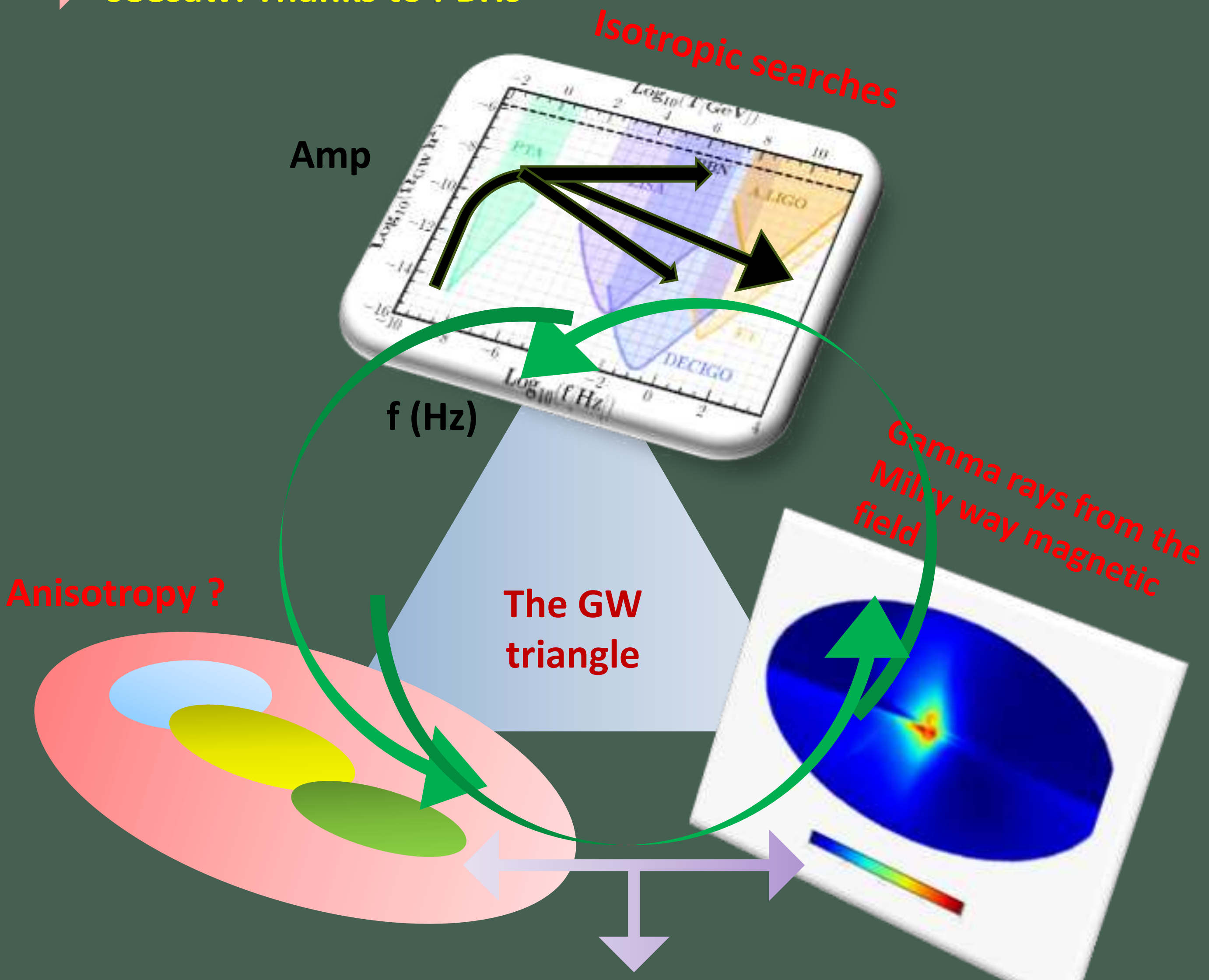


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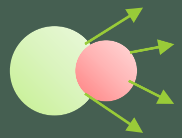
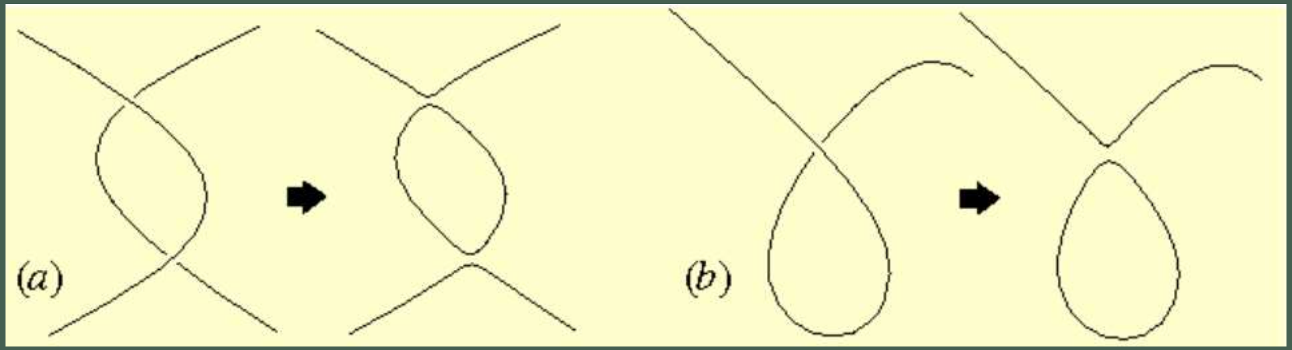
**Analysis of spectral features and search imprints of models**

f (nHz) — f (mHz) — f (Hz)

PTA — LISA — LIGO

**Sources**

| 1st order PT | Primordial Black holes | Cosmic strings |
| --- | --- | --- |
|  | Production, distribution |  |

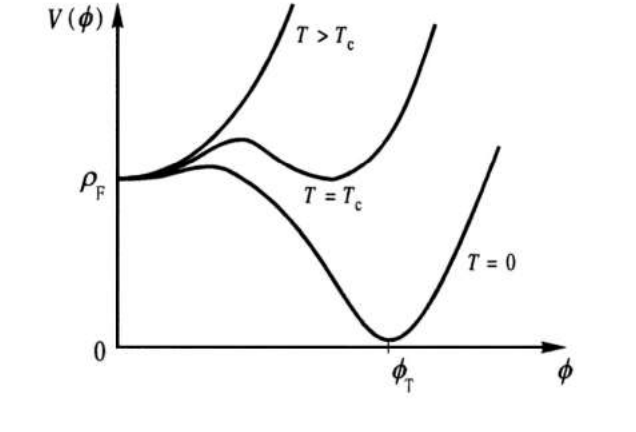


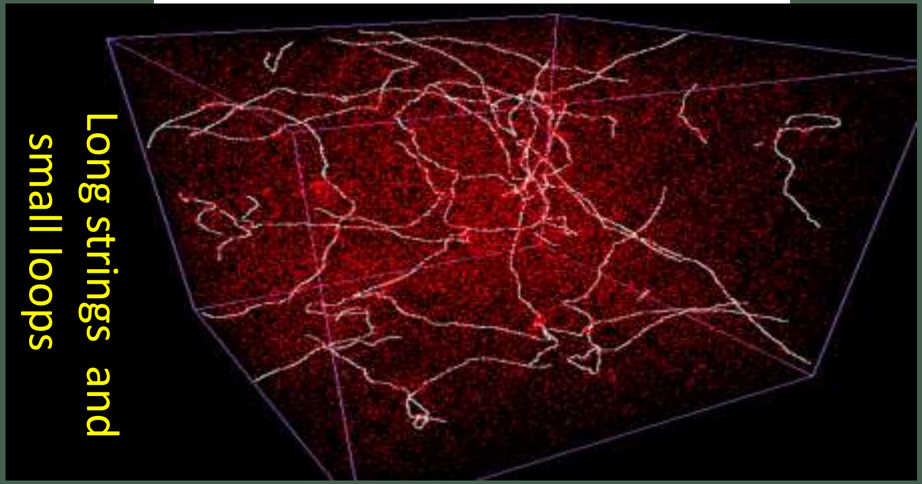

**Formation of cosmic strings needs vacuum not simply connected: U(1)**

T. W. B. Kibble,76

**Effective potential**

$$V(\Phi,T)=\frac{\lambda}{4}\Phi^4+D(T^2-T_0^2)\Phi^2-ET\Phi^3,$$



## Examples and properties

C. J. A. P. Martins and E. P. S. Shellard, Phys. Rev. D 54, 2535-2556 (1996)

**Velocity dependent one-scale model**

**Gauge strings:** GUT models-> $U(1)_{B-L}$

**Global strings:** axion strings

$$\frac{d\rho_\infty}{dt} = -2H(1+\bar{v}^2)\rho_\infty - \mu \int_0^\infty l f(l,t) dl$$

**Melting strings:** Feebly coupled field theories (RS et al, JCAP, 2021)

$$f(x) = \tilde{C}\delta(x - \alpha_L \xi),$$

**Width:** $\delta_w : 1/\sqrt{\lambda}\, v$

**Tension:** $\delta_w$ : $G\mu$ $(v\,.\,v)$, G Newton Constant

$$n(\tilde{t}, l_k(\tilde{t})) = \frac{A_r}{\alpha} \frac{(\alpha + \Gamma G\mu)^{3/2}}{\left[l_k(\tilde{t}) + \Gamma G\mu \tilde{t}\right]^{5/2} \tilde{t}^{3/2}}$$

## Scaling regime

Needs normalisation: O(1)

B.Pillado et al, PRD, 2011

Long string energy, $\rho_L \approx$ background energy * $G\mu$

$$n(\tilde{t}, l_k(\tilde{t})) = \frac{0.18}{\left[l_k(\tilde{t}) + \Gamma G\mu \tilde{t}\right]^{5/2} \tilde{t}^{3/2}}.$$

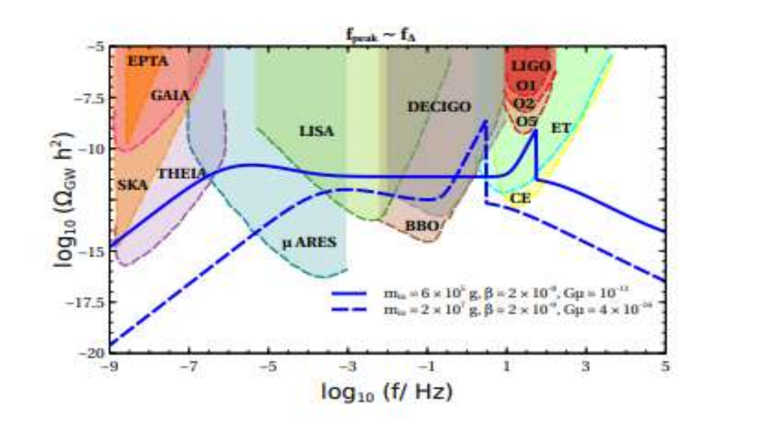
**Cosmic strings never dominate the energy density**

# Gravitational waves from cosmic strings and spectral features

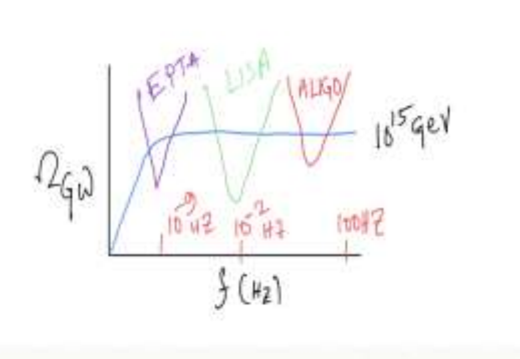
RS et al, 2304.11844

$$\Omega_{GW}^{(k)}(t_0, f) = \frac{2kG\mu^2\Gamma_k}{f\rho_c}\int_{t_F}^{t_0}\left[\frac{a(\tilde{t})}{a(t_0)}\right]^5 n\left(\tilde{t}, \frac{2k}{f}\left[\frac{a(\tilde{t})}{a(t_0)}\right]\right) d\tilde{t}.$$

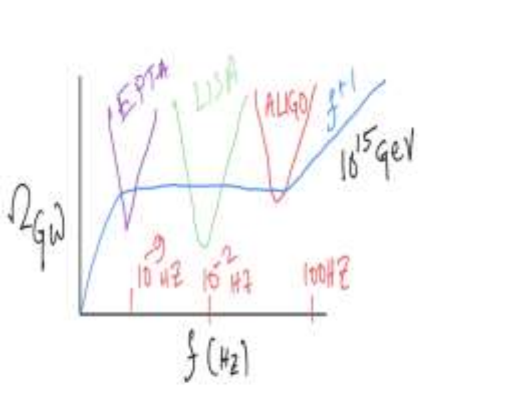
Ultralight PBHs



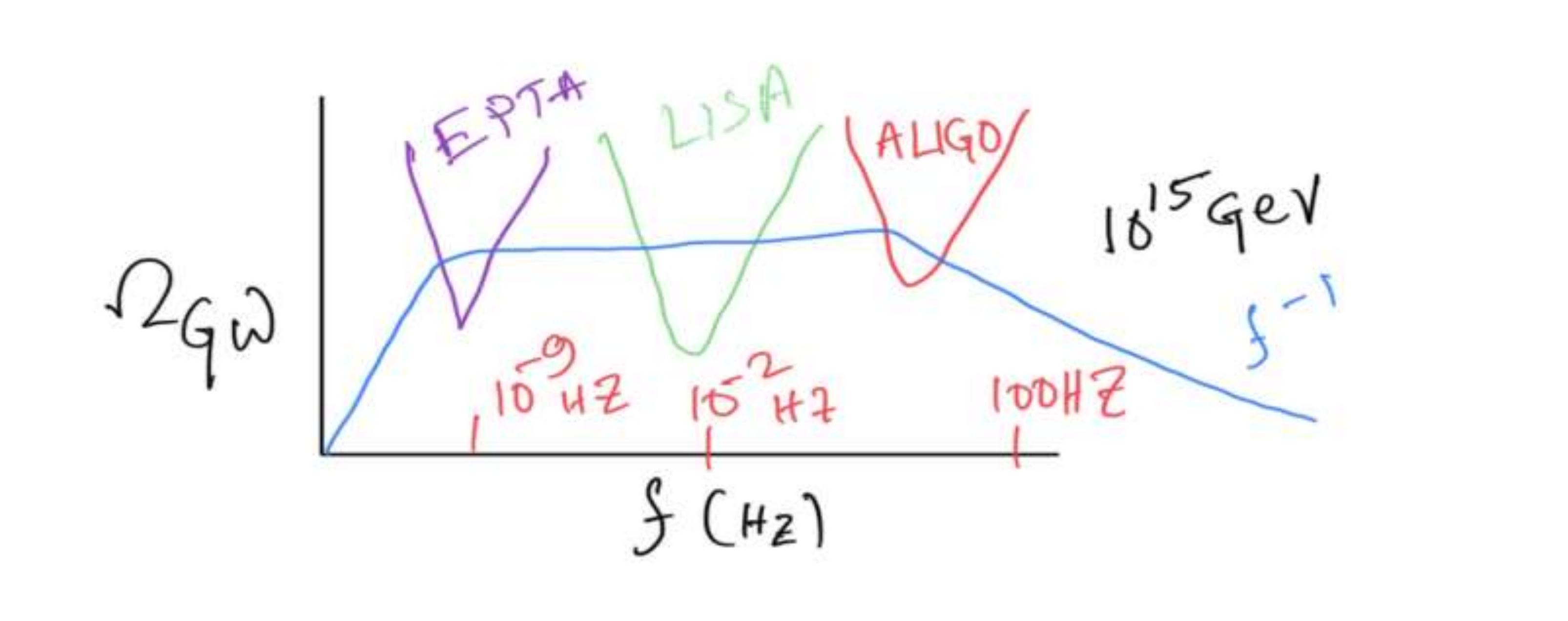

Radiation



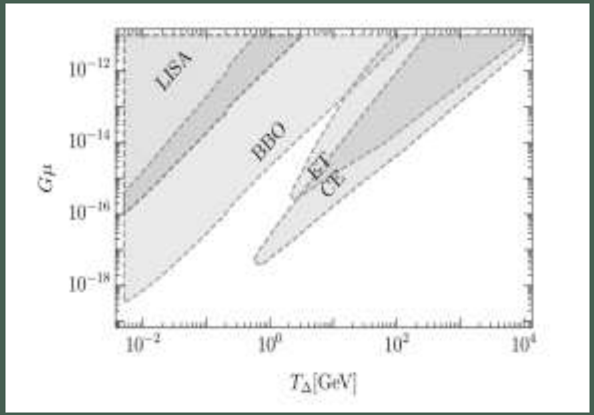

Kination

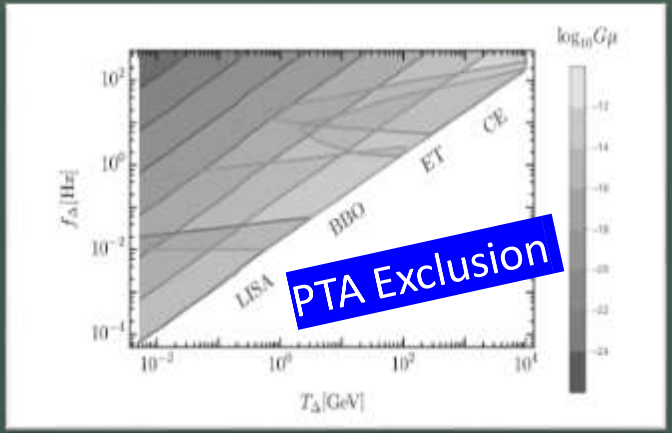



Matter

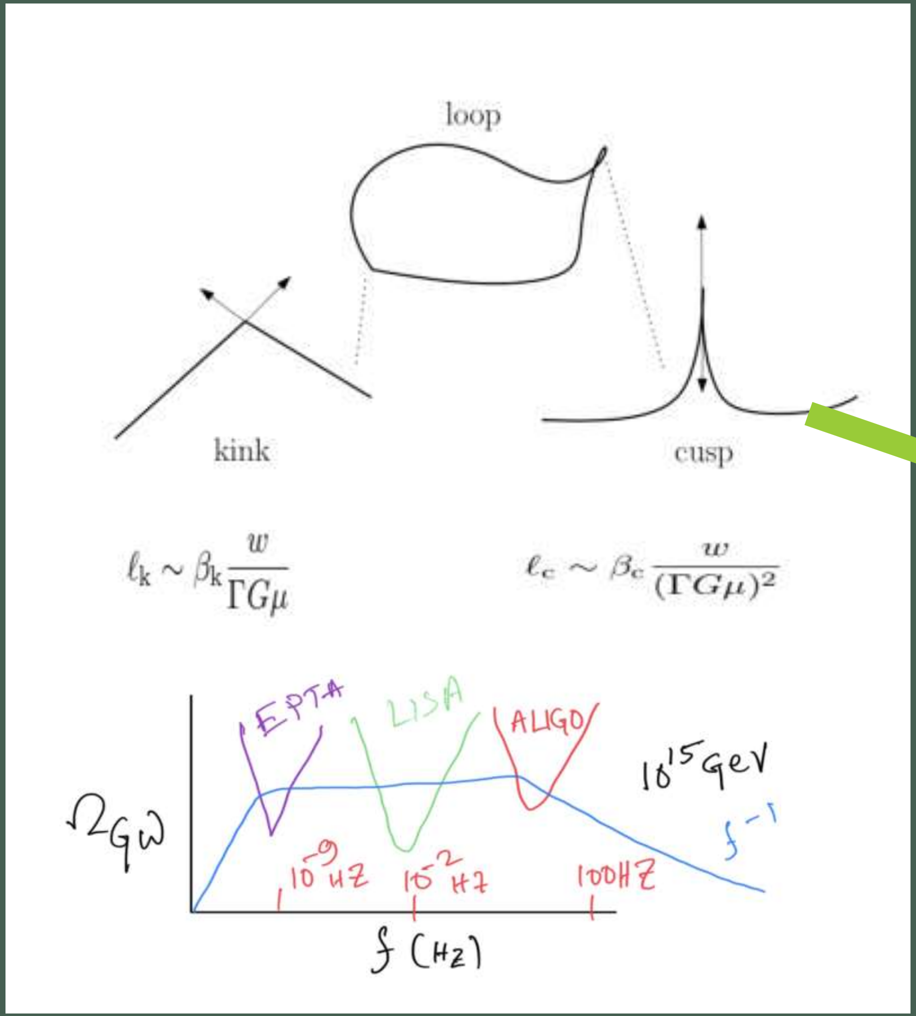


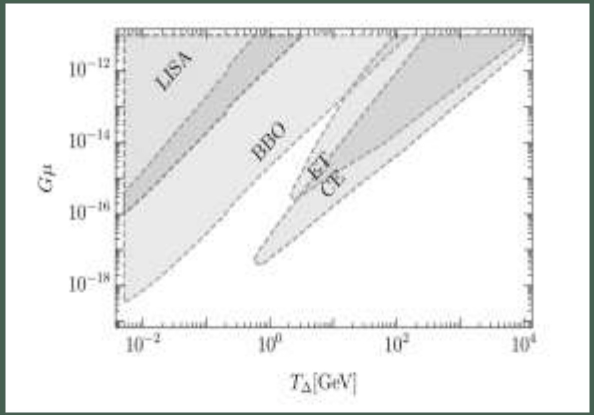
# Gravitational waves from cosmic strings : Mind the sums and cuts

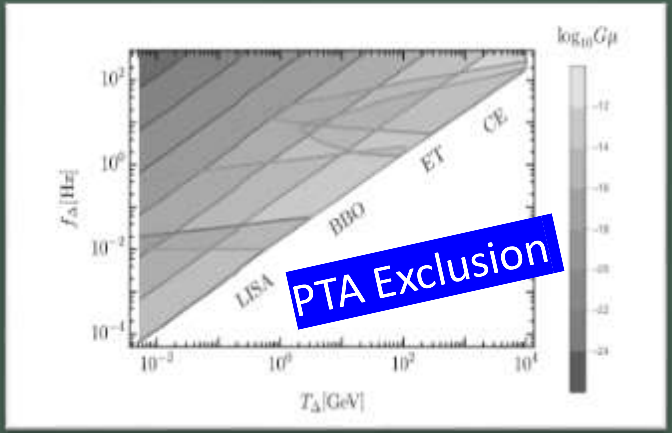


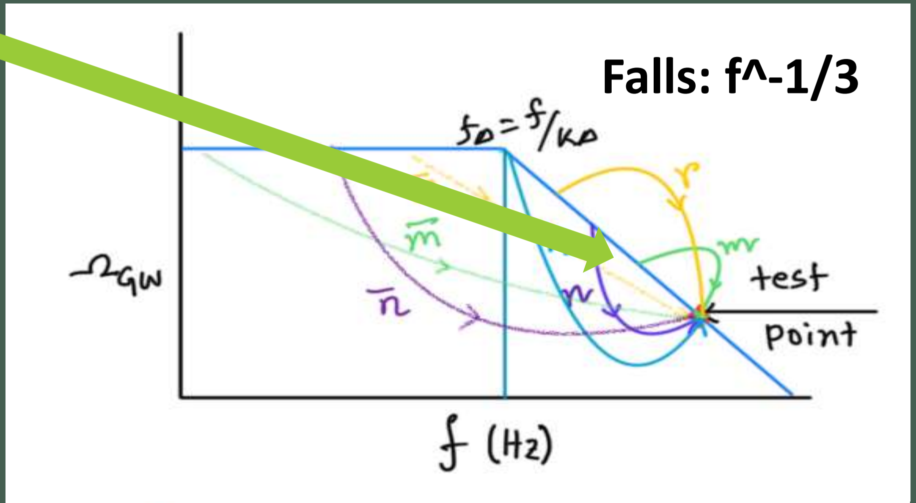



# Gravitational waves from cosmic strings : Mind the sums and cuts




$$\Omega_{GW}(f) = \sum_k k^{-\delta}\Omega^{(1)}(f/k)$$
$$= 1^{-\delta}\Omega^{(1)}(f/1) + m^{-\delta}\Omega^{(1)}(f/m) + n^{-\delta}\Omega^{(1)}(f/n) + r^{-\delta}\Omega^{(1)}(f/r) + ....$$

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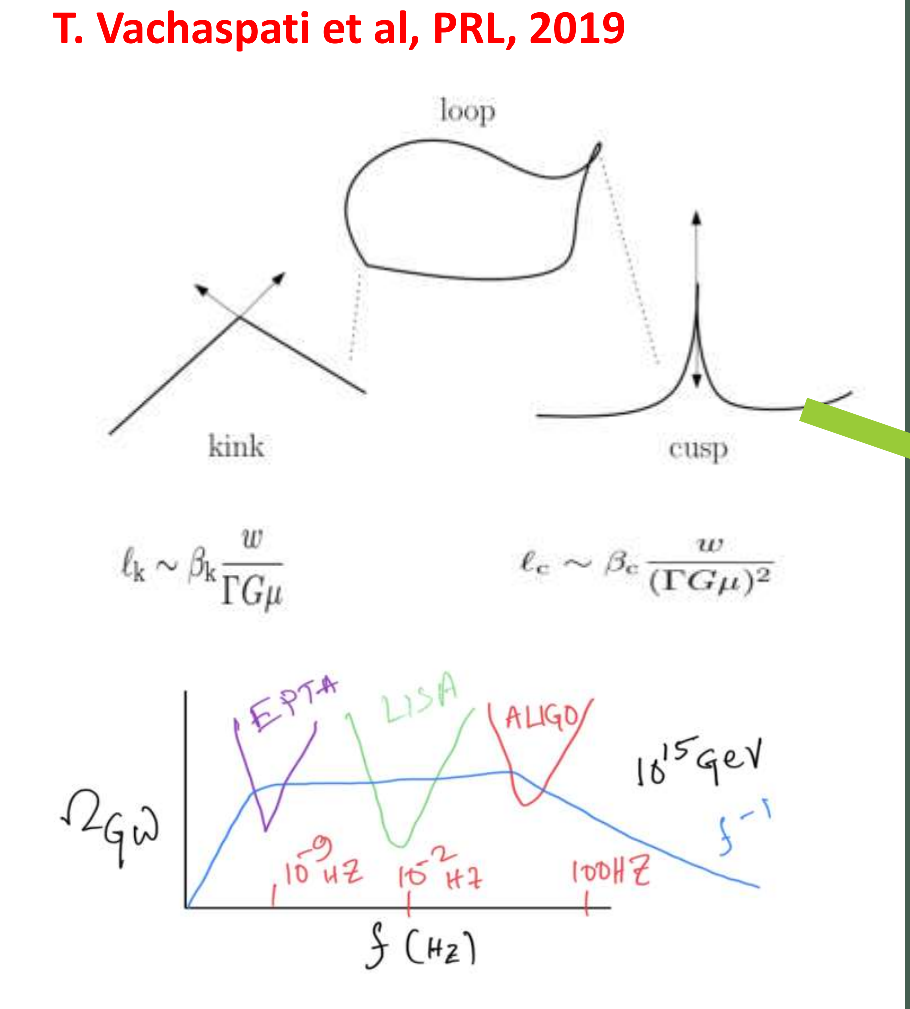


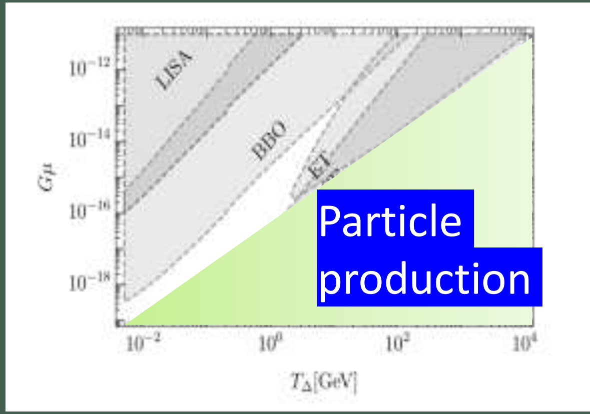


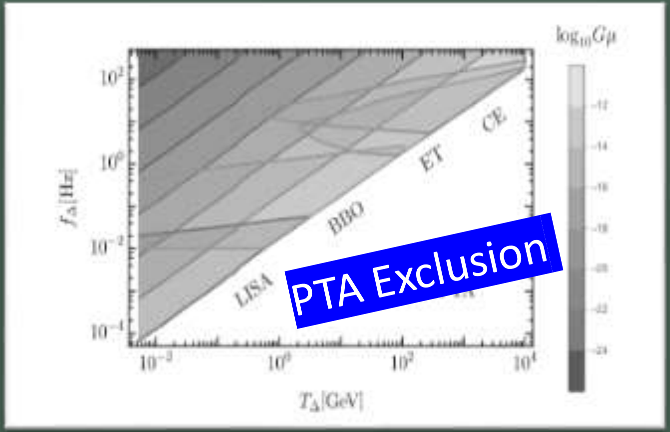


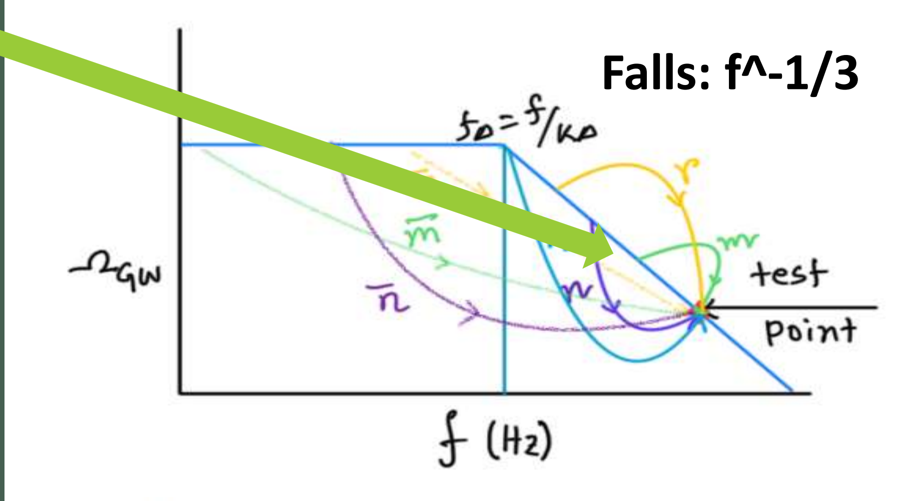


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$$= 1^{-\delta}\Omega^{(1)}(f/1) + m^{-\delta}\Omega^{(1)}(f/m) + n^{-\delta}\Omega^{(1)}(f/n) + r^{-\delta}\Omega^{(1)}(f/r) + \dots,$$

## BSM models: Leptogenesis + right-handed neutrino dark matter

$N_1, N_2, N_3$ : one of them is DM and other two make baryogenesis via leptogenesis

**Models: ɣMSM: active-sterile oscillation**

Asaka, Shaposhnikov, Blanchet, 2005

**$N_3$ : Dark matter mass keV: X-rays**

**RHiNO: Oscillation among N's, e.g., $N_2$ <-> $N_3$**

Di Bari, Ludl, Ruiz, 2016

Di Bari, Farrag, Samanta, Zhou, 2019

**$N_3$ : Dark matter mass PeV: IceCube**

**How heavy $N_i$ could be ?**

**PBH: all of them could be super- heavy;**
**close to GUT scale: GWs**

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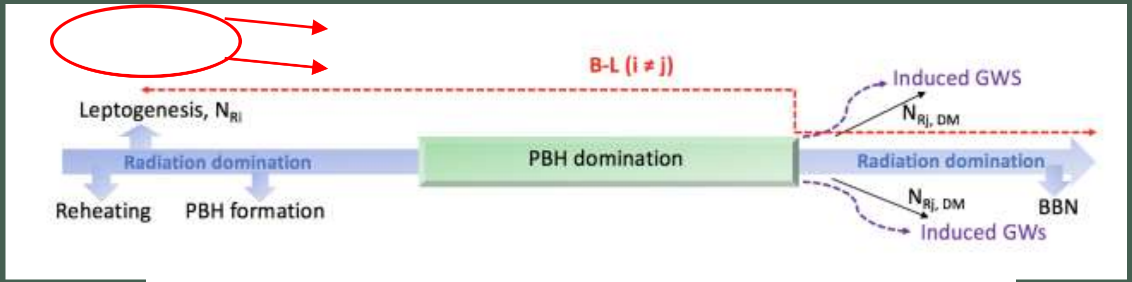
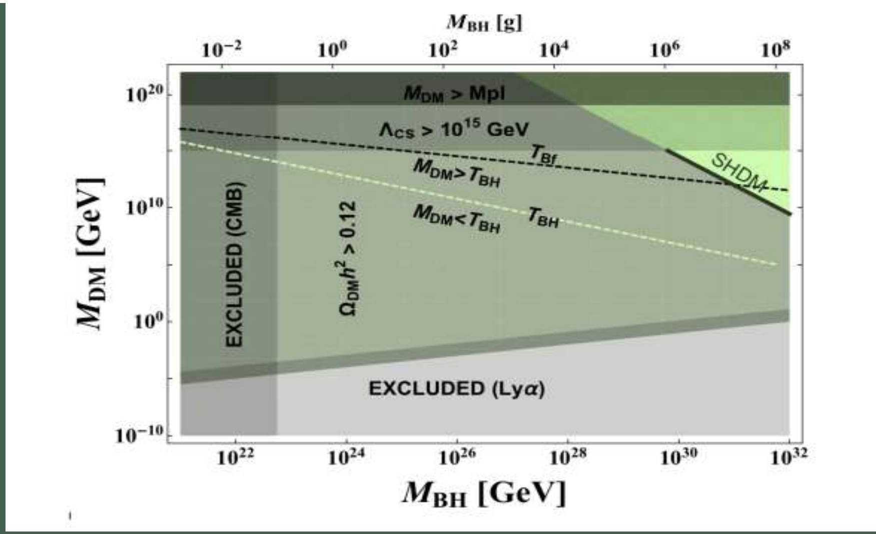



$M_{BH}$ : -> $M_{DM}$, $\beta$:-> M (lepto scale)

Check also: Nicolas, Yuber, Jessica, Lucien, Andrew, Anish, Napoli group papers

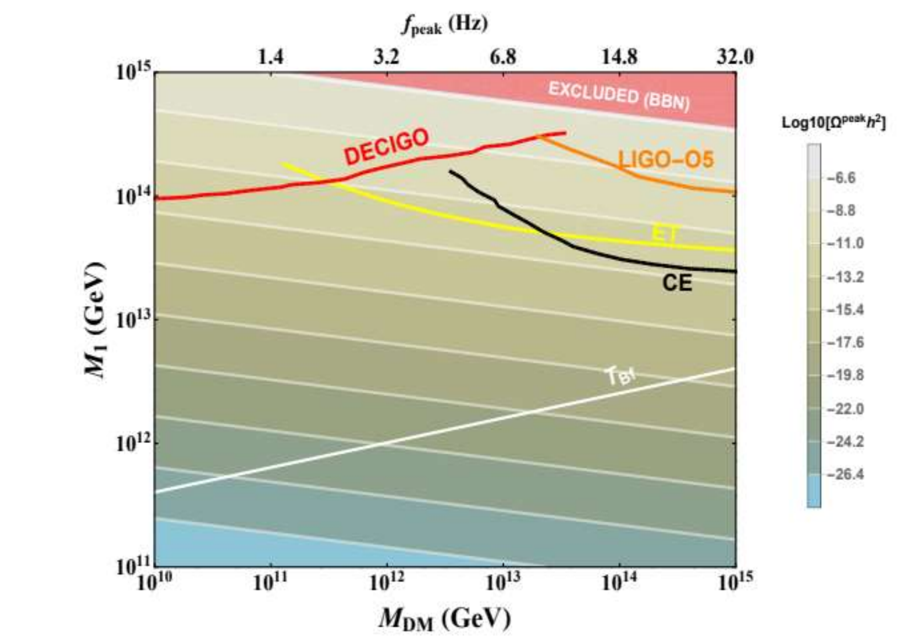
# PBH-seesaw mapping

GWs: Theodoros et al, JCAP(2021)
Domenech et al, JCAP (2021)

$$\beta = 5.7 \times 10^{-12} \left(\frac{M_{\rm Pl}}{M_{\rm BH}}\right) M_1 \ {\rm GeV}^{-1},$$

$$M_{\rm DM} \simeq 4.5 \times 10^{3} \left(\frac{M_{\rm BH}}{M_{\rm Pl}}\right)^{-5/2} M_{\rm Pl}^2 \ \ {\rm GeV}^{-1}$$

RS et al, JHEP 2023



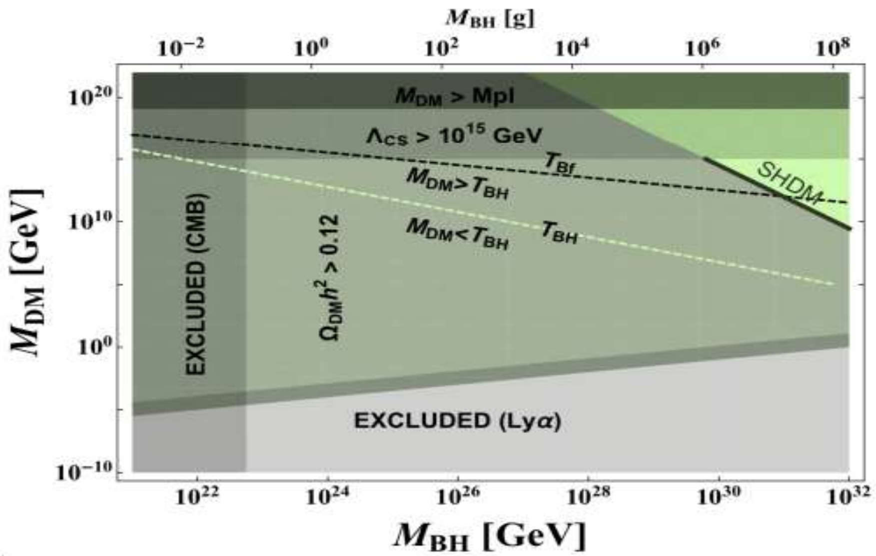

Master equation:

$$\Omega_{\rm GW}^{\rm peak} \simeq \Omega_{\rm GW}^{0} \left(\frac{M_1}{10^{14}\ {\rm GeV}}\right)^{16/3} \left(\frac{M_{\rm DM}}{10^{14}\ {\rm GeV}}\right)^{28/45}$$

# The red-tilt frequency

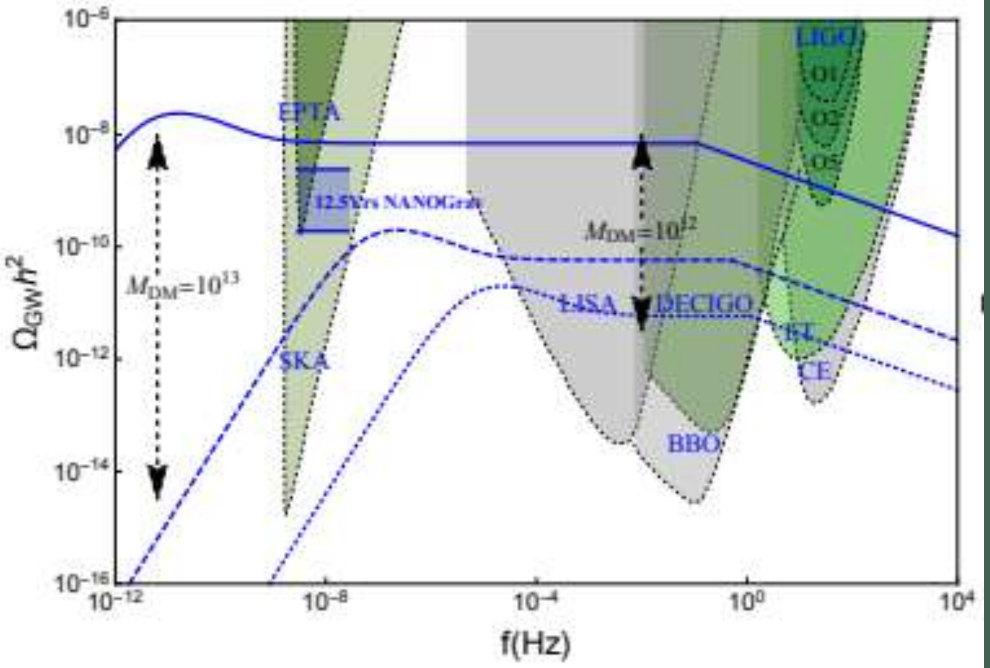
$$T_{ev} = \left( \frac{45 M_{Pl}^2}{16\pi^3 g_*(T_{ev}) \tau^2} \right)^{1/4} .$$

$$\tau = \int_{t_{Bf}}^{t_{ev}} dt = - \int_{M_{BH}}^{0} dM_{BH} \frac{30720\pi M_{BH}^2}{\mathcal{G} g_{*B}(T_{BH}) M_{Pl}^4} = \frac{10240\pi M_{BH}^3}{\mathcal{G} g_{*B}(T_{BH}) M_{Pl}^4} .$$




**√ μ ~ MDM**

$$f_* \simeq 2.1 \times 10^{-8} \sqrt{\frac{50}{z_{eq}\alpha\Gamma G\mu}} \left( \frac{M_{DM}}{T_0} \right)^{3/5} T_0^{-2/5} t_0^{-1},$$

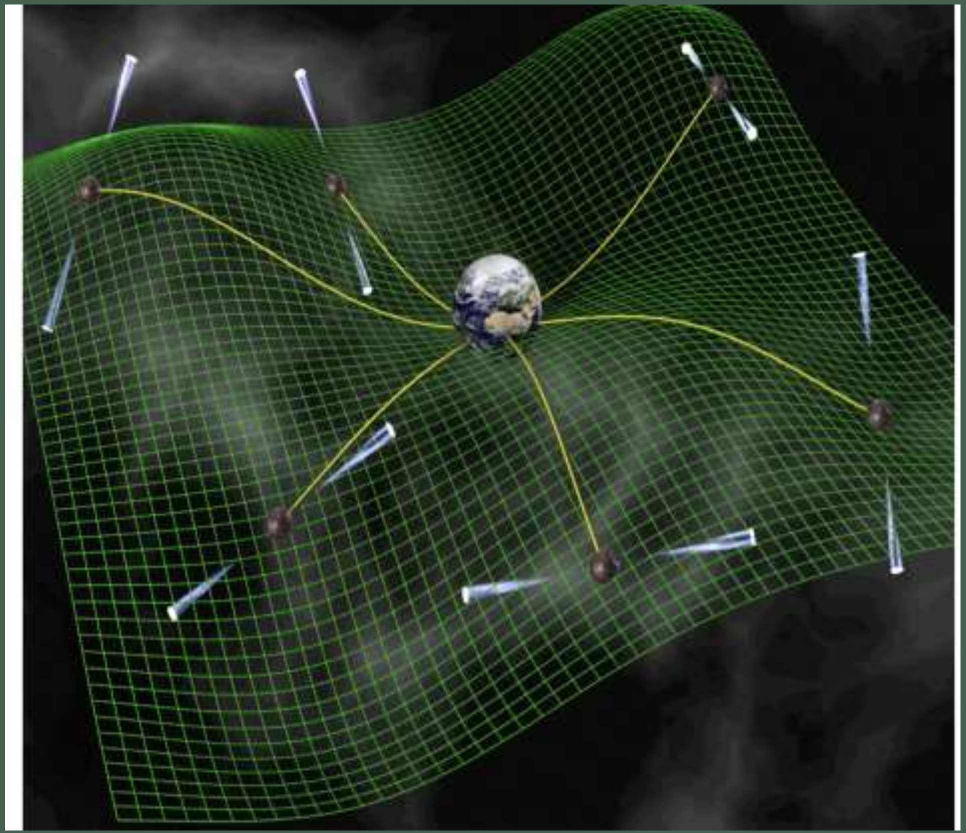


# Why strong amplitude GWs are of interest? PTAs to LIGO

**Millisecond pulsars (spins ~100 times a second) produce most stable pulses and are used by the PTAs**

When a gravitational wave (a disturbance) passes through the earth and pulsar system, the time of arrival of the signal from the pulsars changes. This induces a change in frequency due to the gravitational wave.

Time residual: $$R(t) = -\int_0^t \frac{\delta\nu}{\nu}\,\mathrm{d}t$$



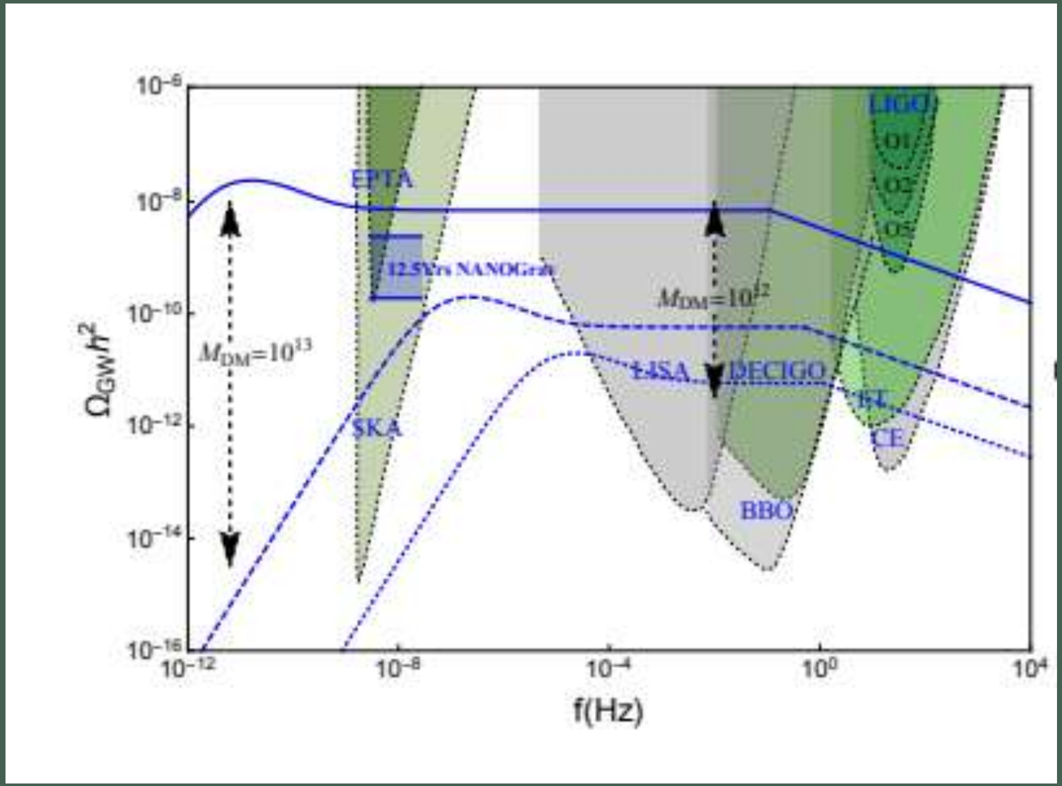
**Pulsar-Timing-Arrays work with high amplitude GWs**

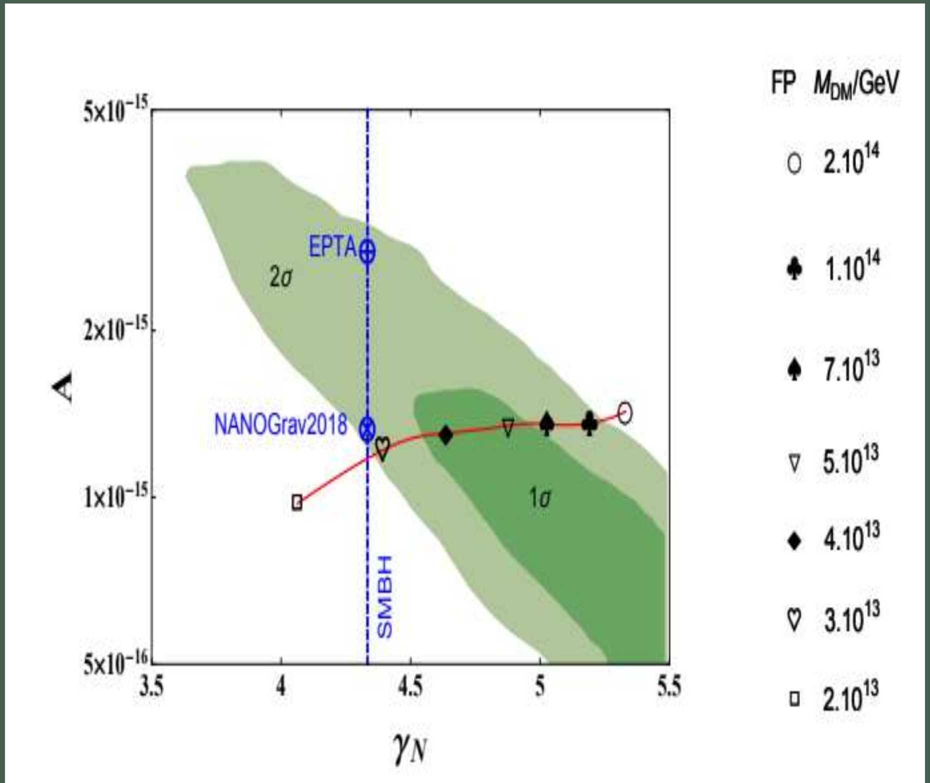
=> Could be a Detector of High Scale Symmetry breaking theories

# NANOGrav-fit

$$\Omega_{GW}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c(f)^2 = \Omega_{yr}\left(\frac{f}{f_{yr}}\right)^{5-\gamma}, \quad \text{with} \quad \Omega_{yr} = \frac{2\pi^2}{3H_0^2} A^2 f_{yr}^2.$$

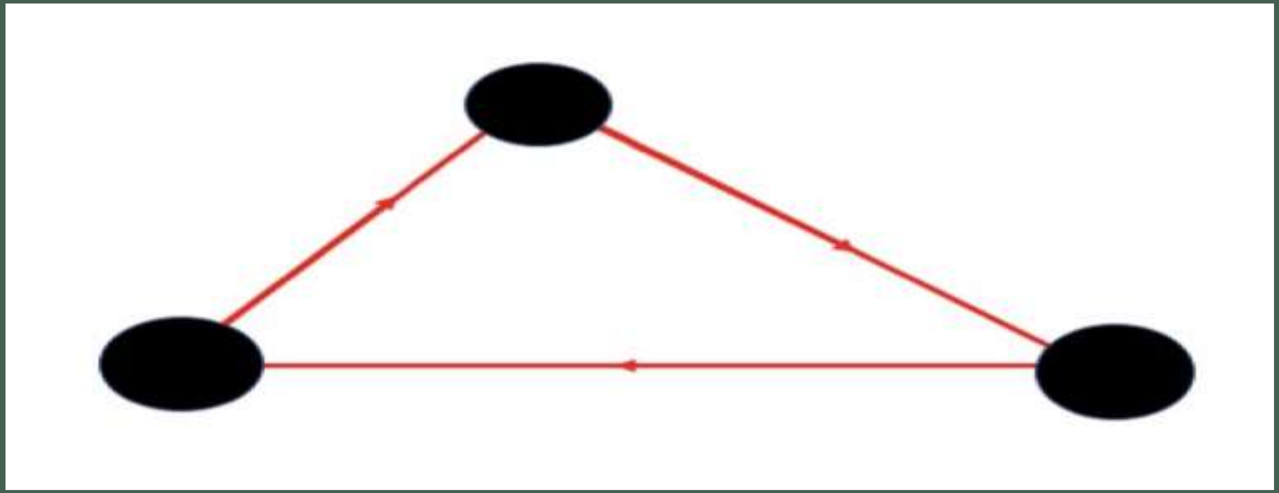
RS et al, JCAP 2022



# caveats

1) Need numerical simulation to check consistency
2) Precise understanding of PBH-string interactions
3) We did not consider black hole-string network that could provide spectral distortion.



# Ultralight PBH dynamics (only non-rotating)

Consider formation in the radiation domination

Mass:

$$M_{BH} = \gamma \frac{4}{3}\pi (H_{Bf}^{-1})^3 \rho_{Bf} \text{ with } \rho_{Bf} = \frac{3H_{Bf}^2 M_{Pl}^2}{8\pi}, \quad H_{Bf} = \frac{1}{2t_{Bf}}.$$

Mass loss:

$$-\frac{dM_{BH}}{dt} = f_{ev}(4\pi r_{BH}^2)\frac{dE}{dt},$$

$$\frac{dM_{BH}}{dt} = -\frac{\mathcal{G} g_{*B}(T_{BH})}{30720\pi}\frac{M_{Pl}^4}{M_{BH}^2},$$

Life-time:

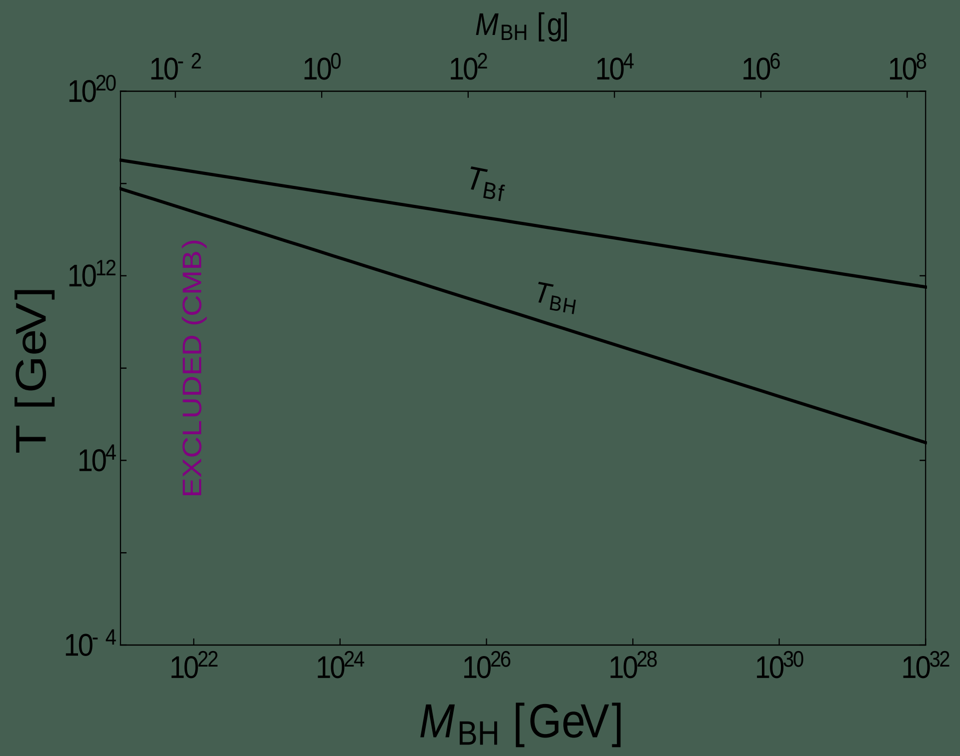
$$\tau = \int_{t_{Bf}}^{t_{ev}} dt = -\int_{M_{BH}}^{0} dM_{BH} \frac{30720\pi M_{BH}^2}{\mathcal{G} g_{*B}(T_{BH}) M_{Pl}^4} = \frac{10240\pi M_{BH}^3}{\mathcal{G} g_{*B}(T_{BH}) M_{Pl}^4}.$$

Evaporation

$$T_{ev} = \left(\frac{45 M_{Pl}^2}{16\pi^3 g_*(T_{ev})\tau^2}\right)^{1/4}.$$

Formation temperature

$$T_{Bf} = \left(\frac{45\gamma^2}{16\pi^3 g_*(T_{Bf})}\right)^{1/4}\left(\frac{M_{Pl}}{M_{BH}}\right)^{1/2} M_{Pl}.$$



## Constraints on black hole masses masses

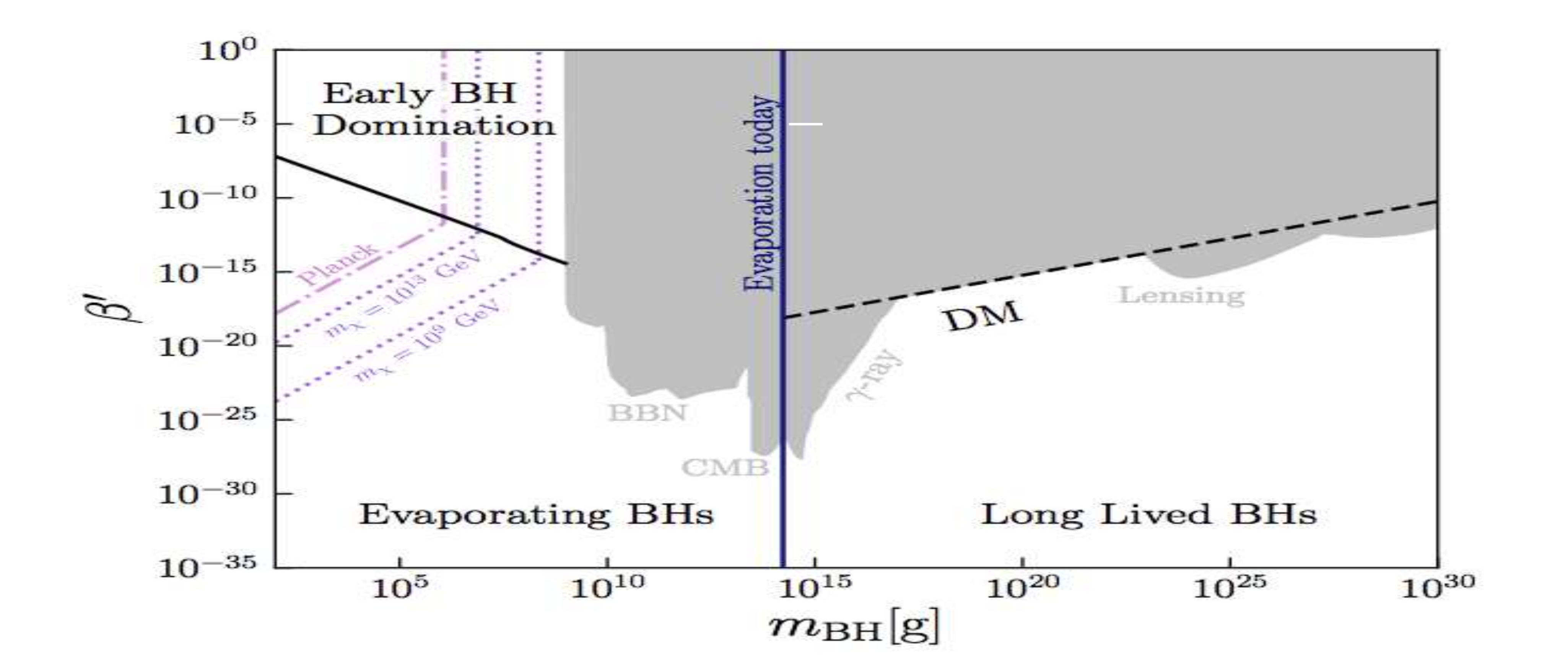
Free parameter: $\beta = \rho_{BH}/\rho_{rad}$

PBH Mass

< 0.1 g (CMB) produce Dark matter

>$10^9$ g (constrained by BBN T~5MeV)

> $10^{15}$ g (it-self Dark matter)



# Ultralight PBH dynamics (only non-rotating)

Black holes not to dominate:

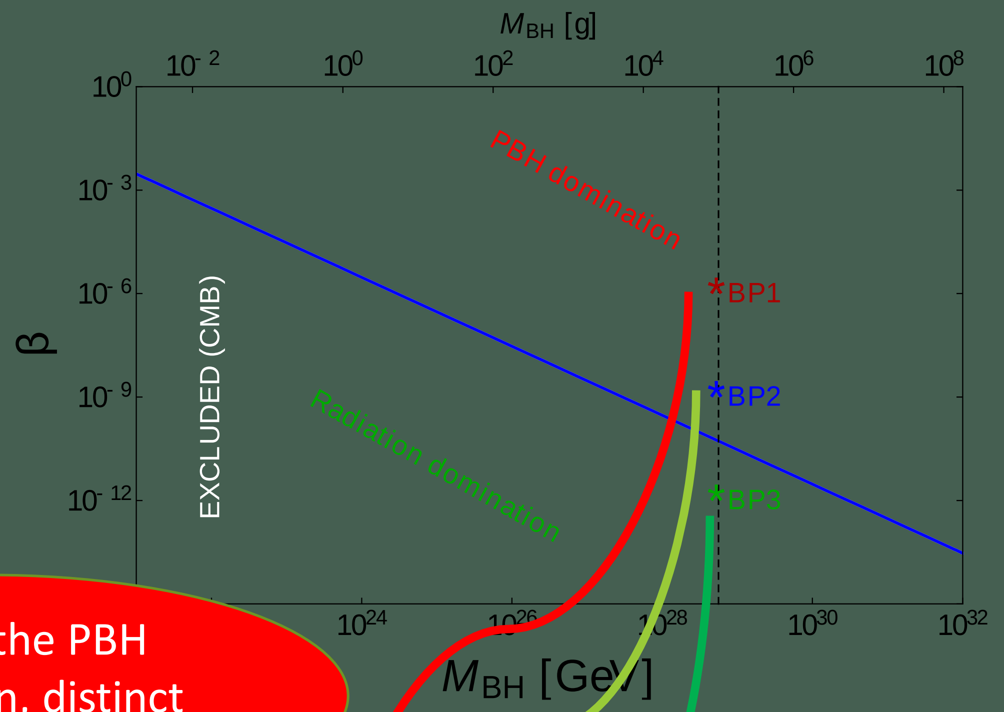
$$\beta < \gamma^{-1/2}\left(\frac{\mathcal{G} g_{*B}(T_{BH})}{10240\pi}\right)^{1/2}\frac{M_{Pl}}{M_{BH}}.$$

**Kinetic equations:**

$$\frac{d\rho_R}{dt} + 4H\rho_R = -\frac{\dot{M}_{BH}}{M_{BH}}\rho_{BH},$$

$$\frac{d\rho_{BH}}{dt} + 3H\rho_{BH} = +\frac{\dot{M}_{BH}}{M_{BH}}\rho_{BH},$$

$$\frac{ds}{dt} + 3Hs = -\frac{\dot{M}_{BH}}{M_{BH}}\frac{\rho_{BH}}{T},$$




Deep in the PBH domination, distinct GW spectral feature